Spacecraft charging via numerical simulations

G.L. Delzanno

Collaborators: C.S. Meierbachtol, J.D. Moulton, D. Svyatsky, L.J. Vernon, J.E. Borovsky, M.F. Thomsen

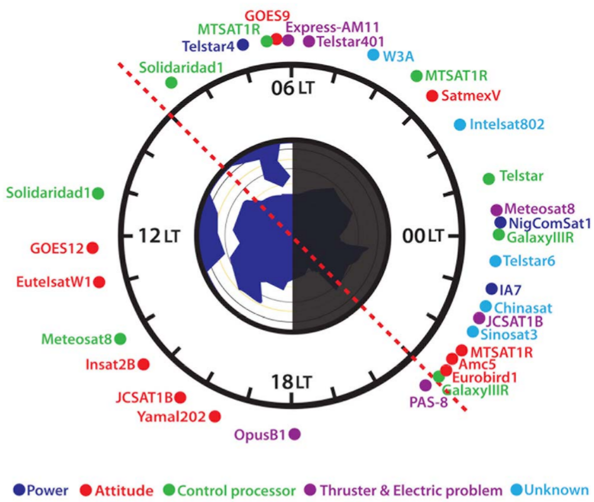
Los Alamos NATIONAL LABORATORY EST. 1943

Outline

- Motivation
- Design considerations for plasma-material interaction PIC codes
  - Curvilinear PIC (CPIC)
- Selected examples
- Conclusions

Spacecraft are critical infrastructure threatened by space weather

- Society increasingly rely on spacecraft technology
  - ~1000 sc around Earth
  - ~250 commercial communication sc, $75B investment, $25B/year revenue (+consumer surplus)
- Spacecraft anomalies are common
  - Mild to catastrophic
  - Sometimes associated with environment
  - Very hard to pinpoint origin
  - Seek statistical correlation with data



Choi et al. 2011

- Surface charging primarily on night side
  - Link with substorms: Kp and MLT dependence
  - Correlation with 5-10 keV population [Thomsen et al, SW13]
- Simulations to identify probable cause
  - Need environment and sophisticated charging tools

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Plasma-material interaction (PMI) is a multiscale problem, traditionally studied with PIC

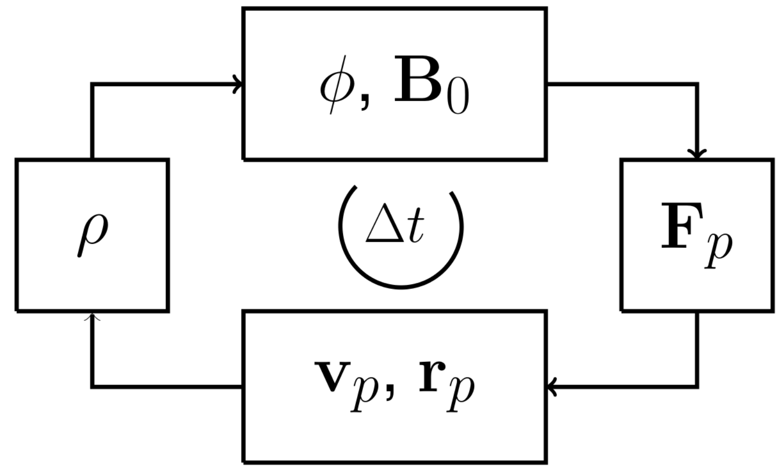
Collisionless, Vlasov-Poisson model:

$$\frac{\partial f_\alpha}{\partial t} + v \cdot \nabla f_\alpha + \frac{\vec{F}_\alpha}{m_\alpha} \cdot \nabla_v f_\alpha = 0$$

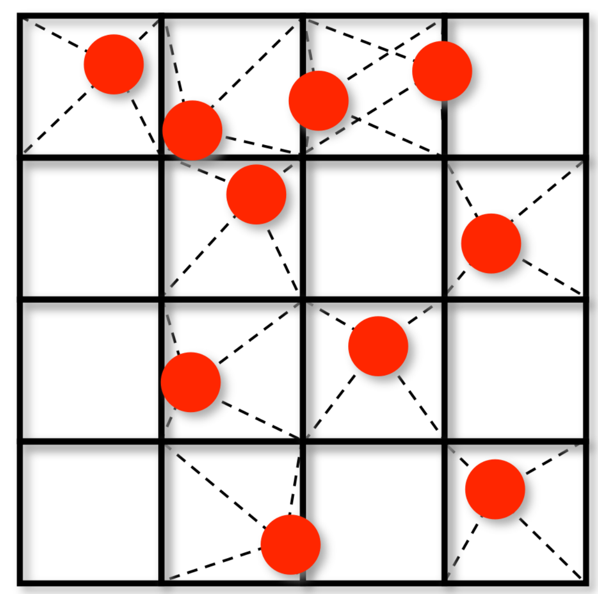
$$\vec{F}_\alpha = q_\alpha \left(-\nabla \phi + \mathbf{v} \times \mathbf{B}_0 \right)$$

$$-\epsilon_0 \nabla^2 \phi = \rho = \sum_\alpha q_\alpha \left[\int f_\alpha d^3 v \right]$$

Particle-In-Cell (PIC) cycle



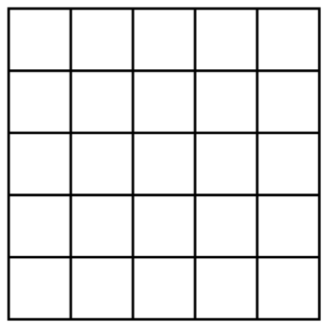
PIC
- Macroparticles
- Computational grid
- Key PIC elements: mesh, solver, mover
- **Multiscale**: Runs can take hours/days/weeks depending on the problem!



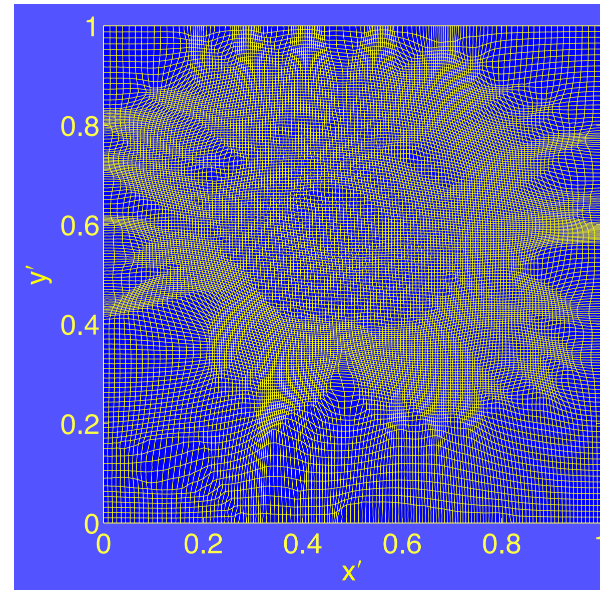
For the field solver, one would want a NON-UNIFORM, structured mesh in a PMI code

- Uniform vs Non-Uniform
  - Avoid small features setting grid scale

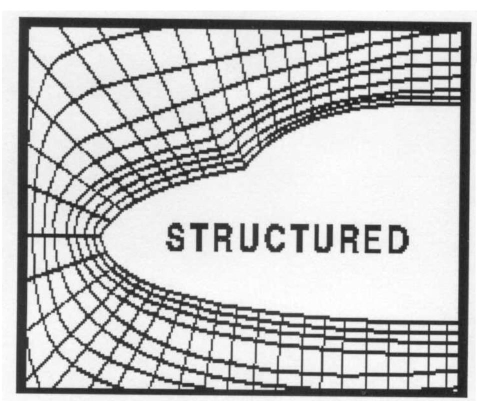
Uniform mesh



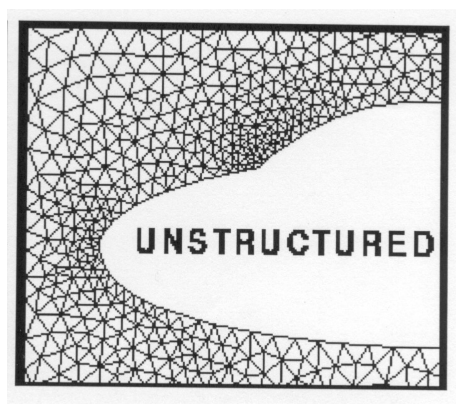
Non-uniform mesh



- Structured vs Unstructured



Fixed pattern,
easy to locate neighbor



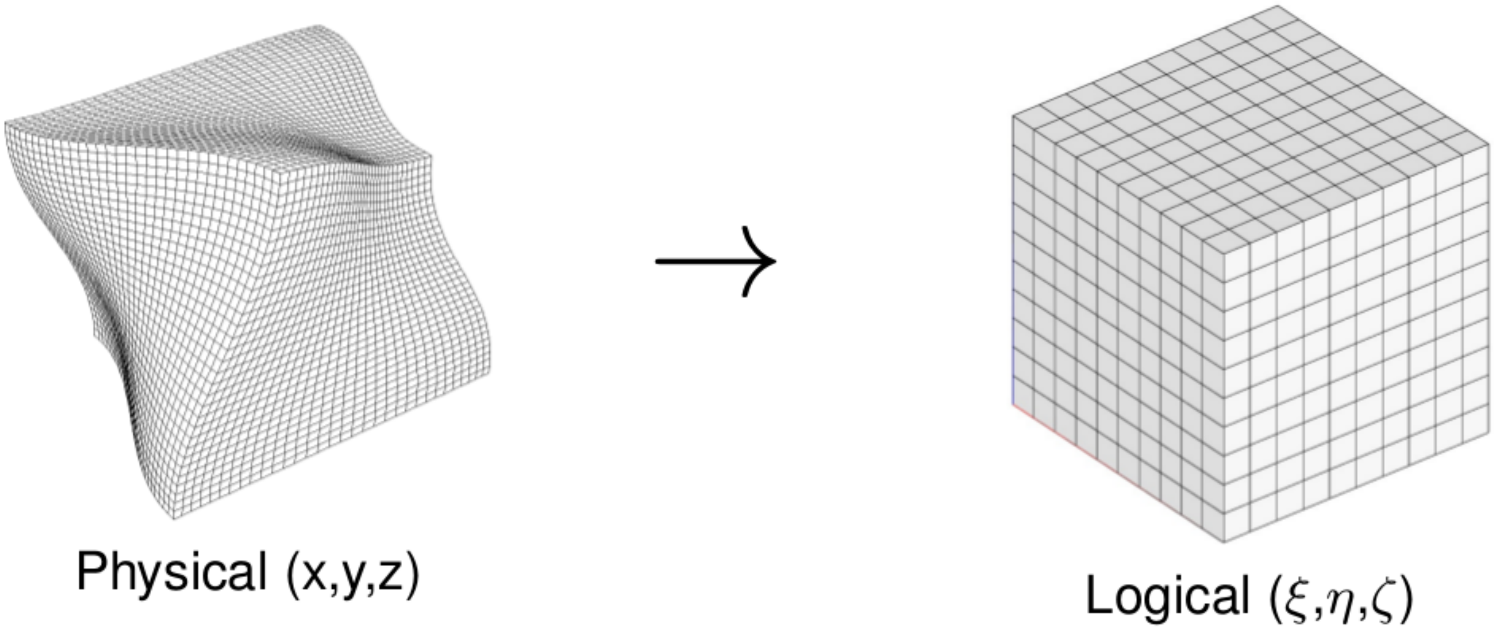
Needs connectivity table

- Unstructured meshes: flexibility
- Faster solvers on structured meshes
  - x5-10 faster for a multigrid solver

MacLachlan et al, JCP 08

For the particles, one would want a UNIFORM, structured mesh in a PMI code

- Uniform vs Non-Uniform
  - Avoid particle-tracking
  - Tracking: x3-5 slower on unstructured mesh



Competitors move particles in physical space

Summary of design choices

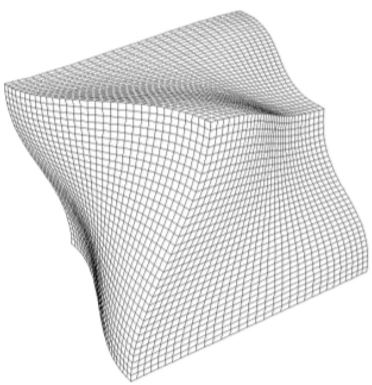
Wish-list

- Solver: Non-uniform, structured mesh
- Particles: Uniform, structured mesh
- Parallelization

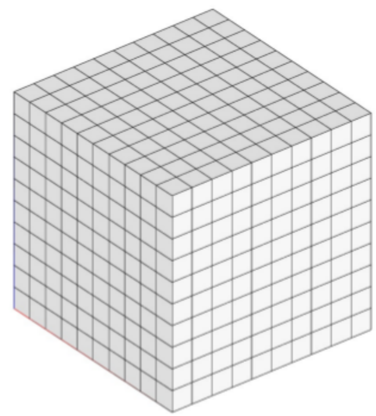
Curvilinear PIC (CPIC) developed at LANL follows these design choices and combines them with modern algorithms to tackle a broader set of problems

PIC with non-uniform mesh for solvers but uniform mesh for particles is possible with coordinate transformation

- Body-fitted logical to physical space mapping
- Coordinate transformation: $\mathbf{x} = \psi(\boldsymbol{\xi})$
  - Physical space variables $\mathbf{x} = (x, y, z)$
  - Logical space variables $\boldsymbol{\xi} = (\xi, \eta, \zeta)$



Physical (x,y,z)



Logical (ξ,η,ζ)

Structured meshes, fast solvers

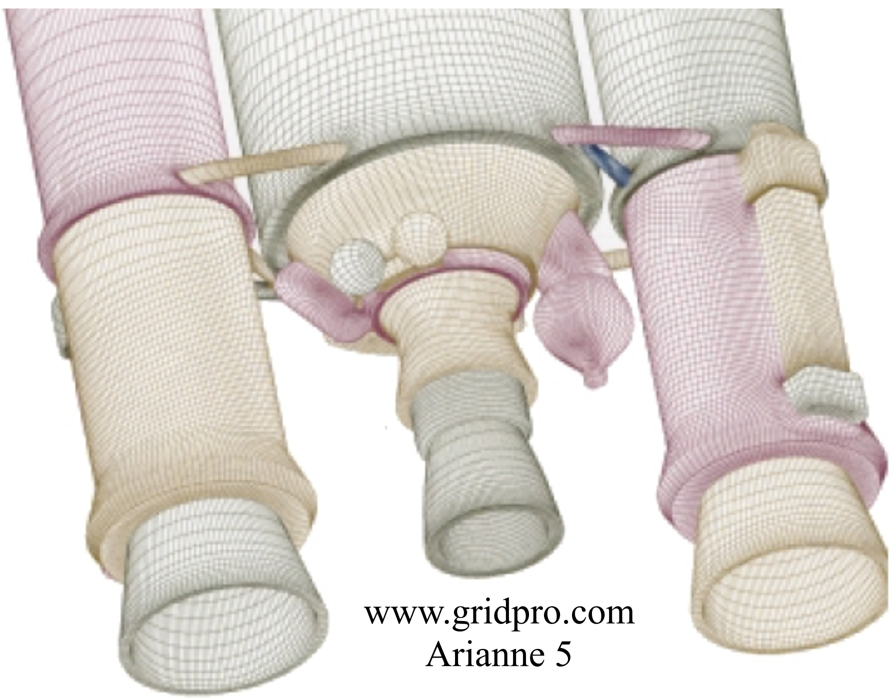
Geometry independent

- Metric elements
  - Jacobi matrix and its inverse, metric tensor
  - Operators in logical space:

$$\nabla^2_{\mathbf{x}}\Phi(\mathbf{x}) = \frac{1}{J}\frac{\partial}{\partial\xi^\alpha}\left(Jg^{\alpha\beta}\frac{\partial\Phi(\boldsymbol{\xi})}{\partial\xi^\beta}\right)$$

Complex objects&structured mesh require multi-block meshes

- Simple geometries easy to handle
- Complex geometries require mesh generators
  - Developed in CFD community
  - Many for unstructured meshes – single-block mesh
  - Commercially available: structured mesh generators
    - Cad files → mesh



www.gridpro.com
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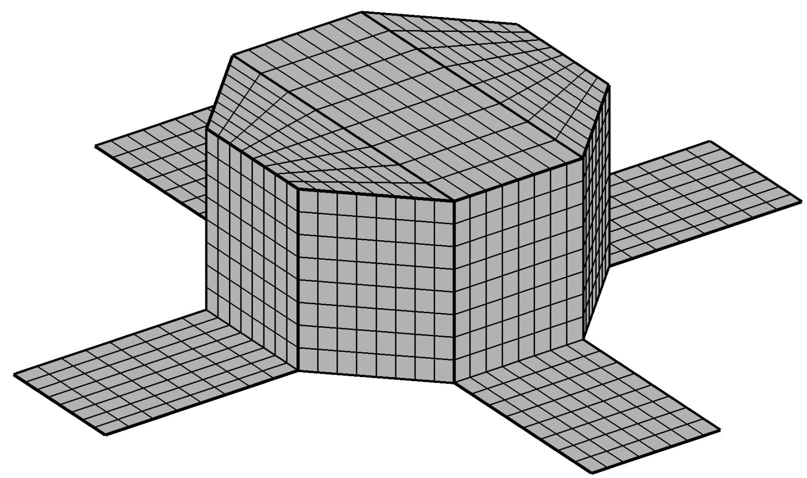
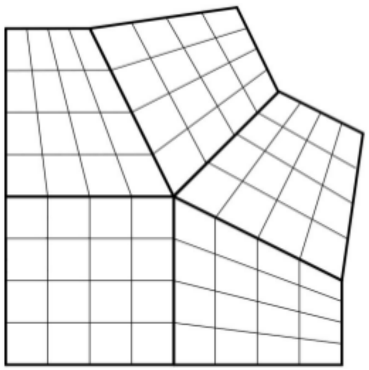


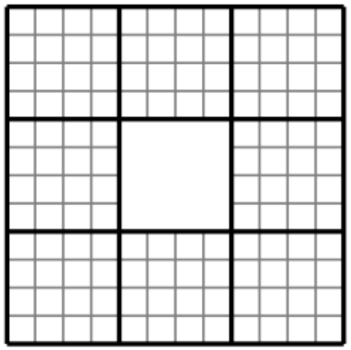
Mesh mimicking the VanAllen Probes sc

Multi-block PIC is far from trivial …

- Many challenges
- Mesh
  - Locally structured, globally unstructured
  - Inter-block face, coordinate orientation
  - Many-block junction points
- Field solver
  - Mimetic discretization [Lipnikov et al., JCP 04]
- Particles
  - Needs to know block
    - More info to be communicated among processors
  - New block orientation



Many-block junction



Internal boundary

… but these challenges have been met in the new version of CPIC

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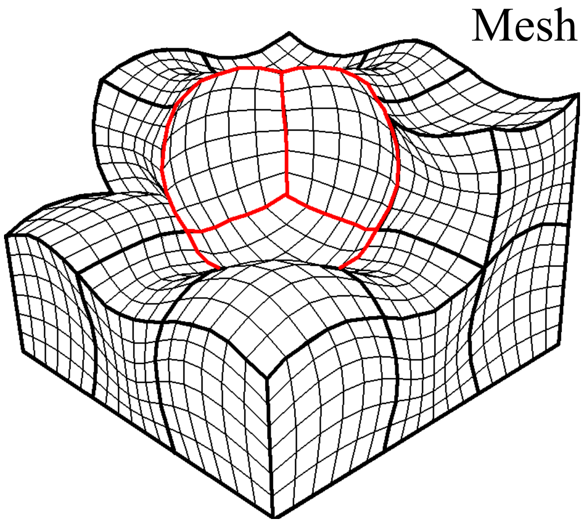
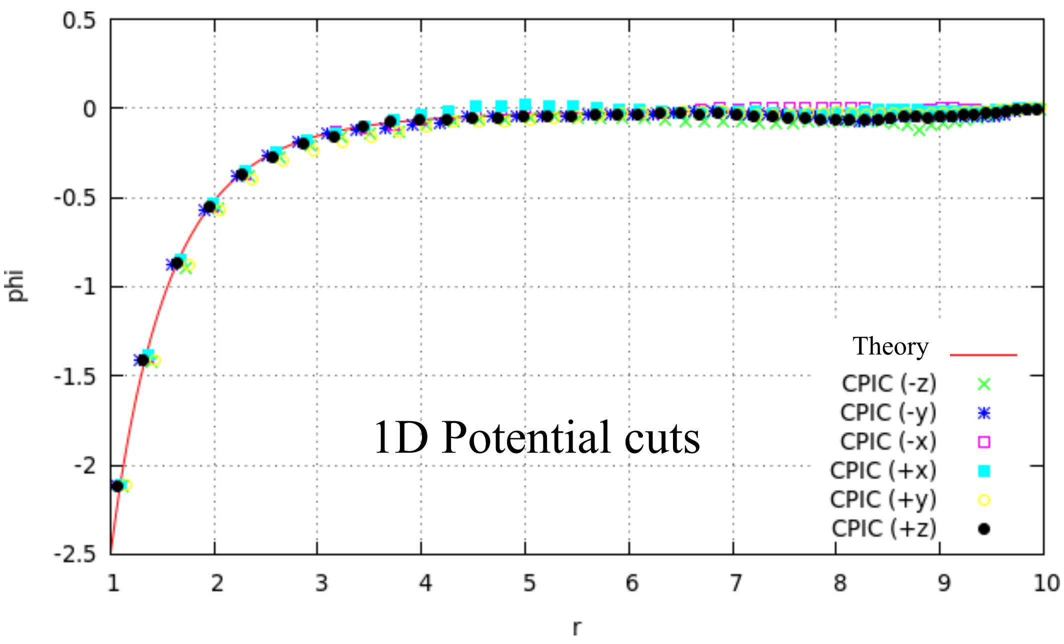
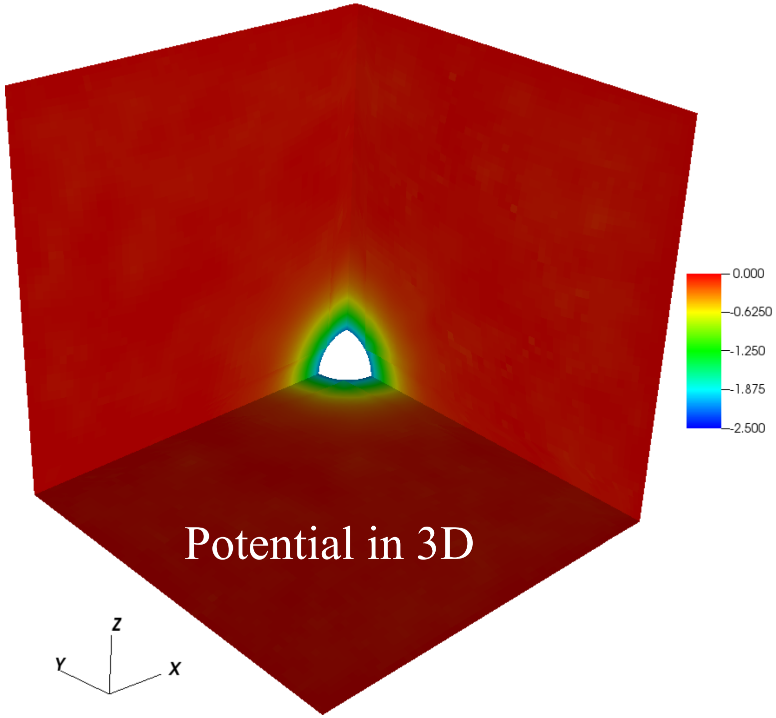
Successful verification on simple charging problem

- Charging of a sphere in a plasma
- Analytic solution exists
- CPIC with multi-block mesh
- Good agreement with theory:

collected currents, symmetry and plasma screening

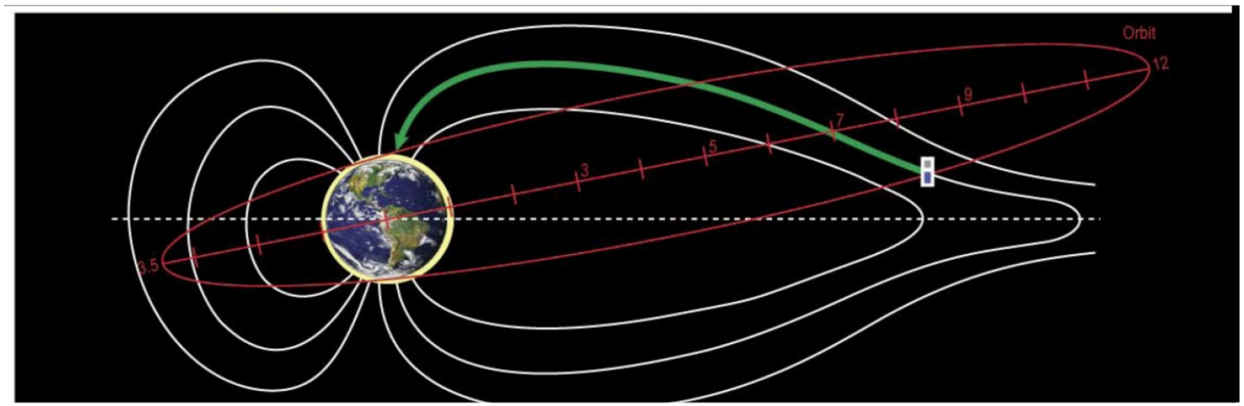






Probing the Earth's magnetosphere with an electron gun

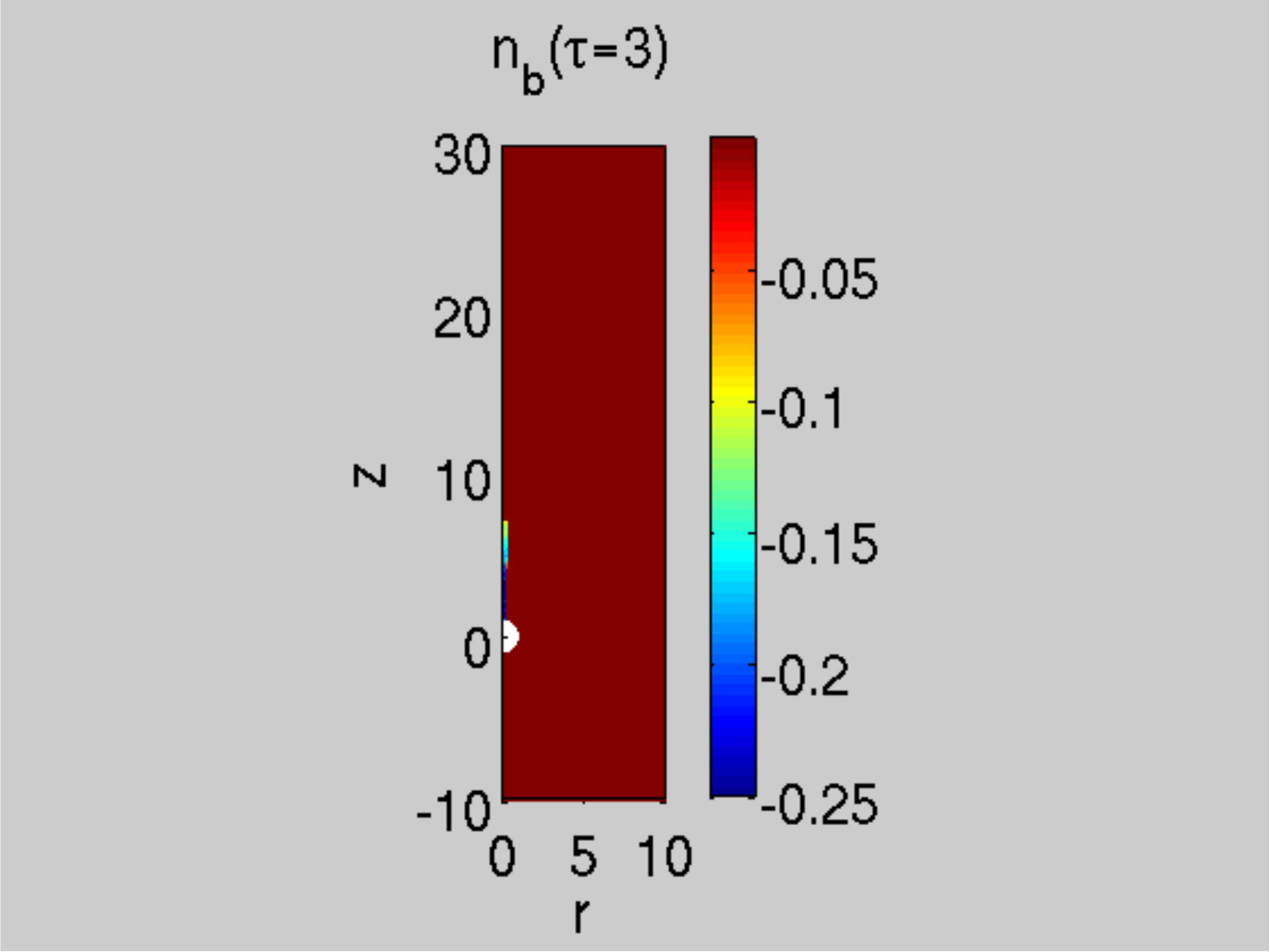
- Goal: establish connectivity of magnetic field lines from the magnetosphere to the ionosphere
- High-power electron beam from magnetospheric spacecraft



- Spacecraft charging is a big problem: I_e~μA, I_B~.1 A

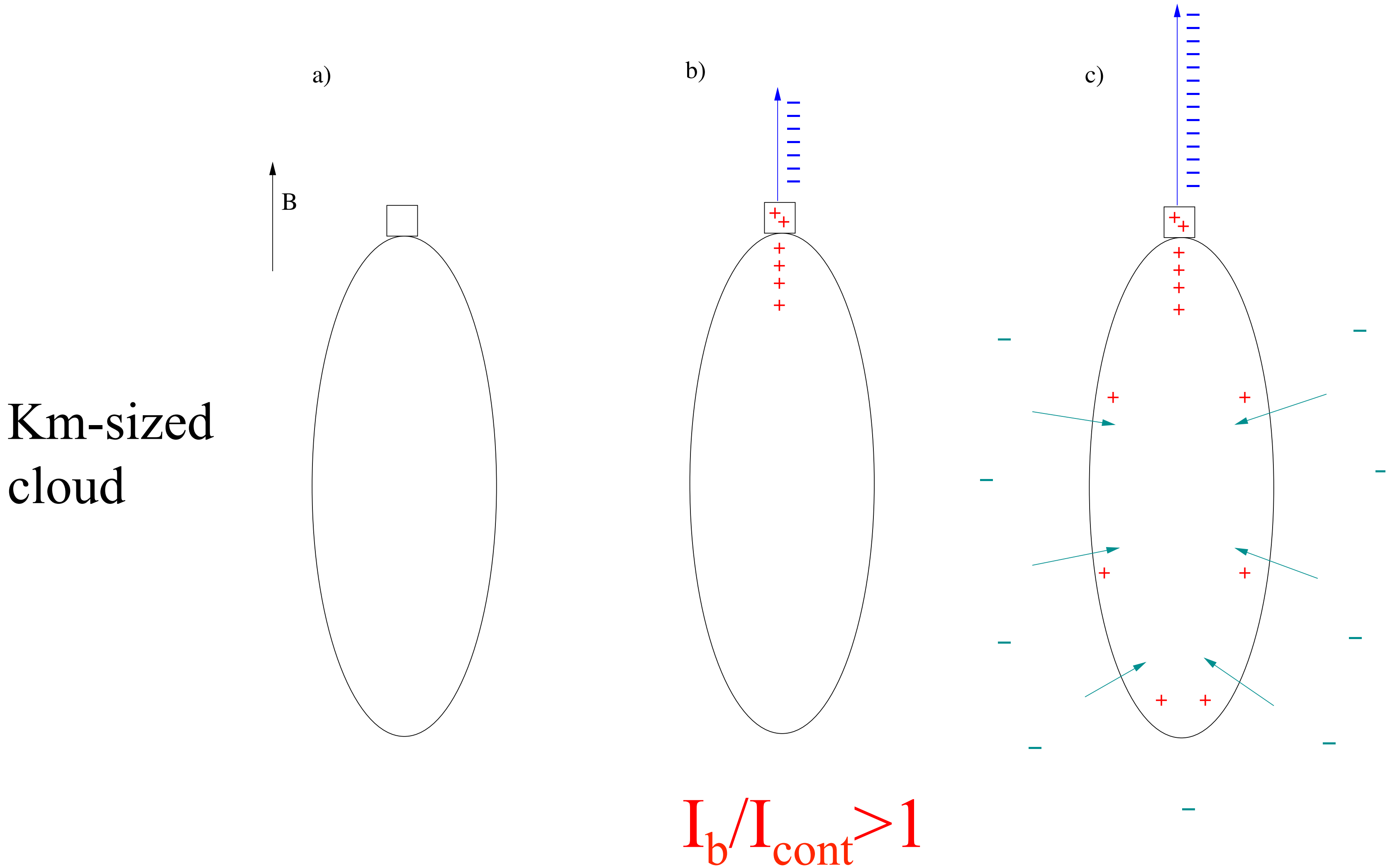
$$\frac{dQ_{sp}}{dt} = I_b^e + I_e^{bg} + I_i^{bg} + I_e^{cont} + I_i^{cont}$$

The beam returns to the spacecraft if spacecraft charging cannot be mitigated



Charging mitigation with a plasma contactor, used to increase electron collection …

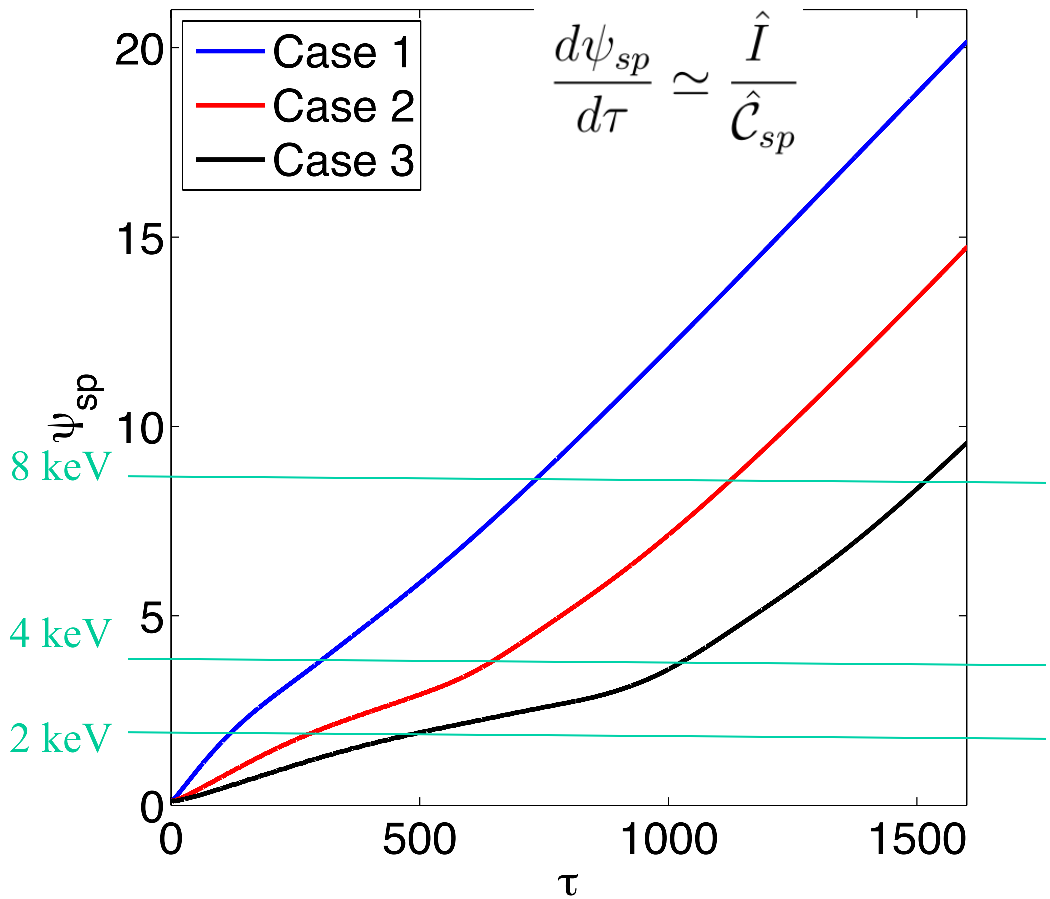
- Plasma contactor: provides a high density plasma reservoir



… would not work! $I_b/I_{cont}=2$

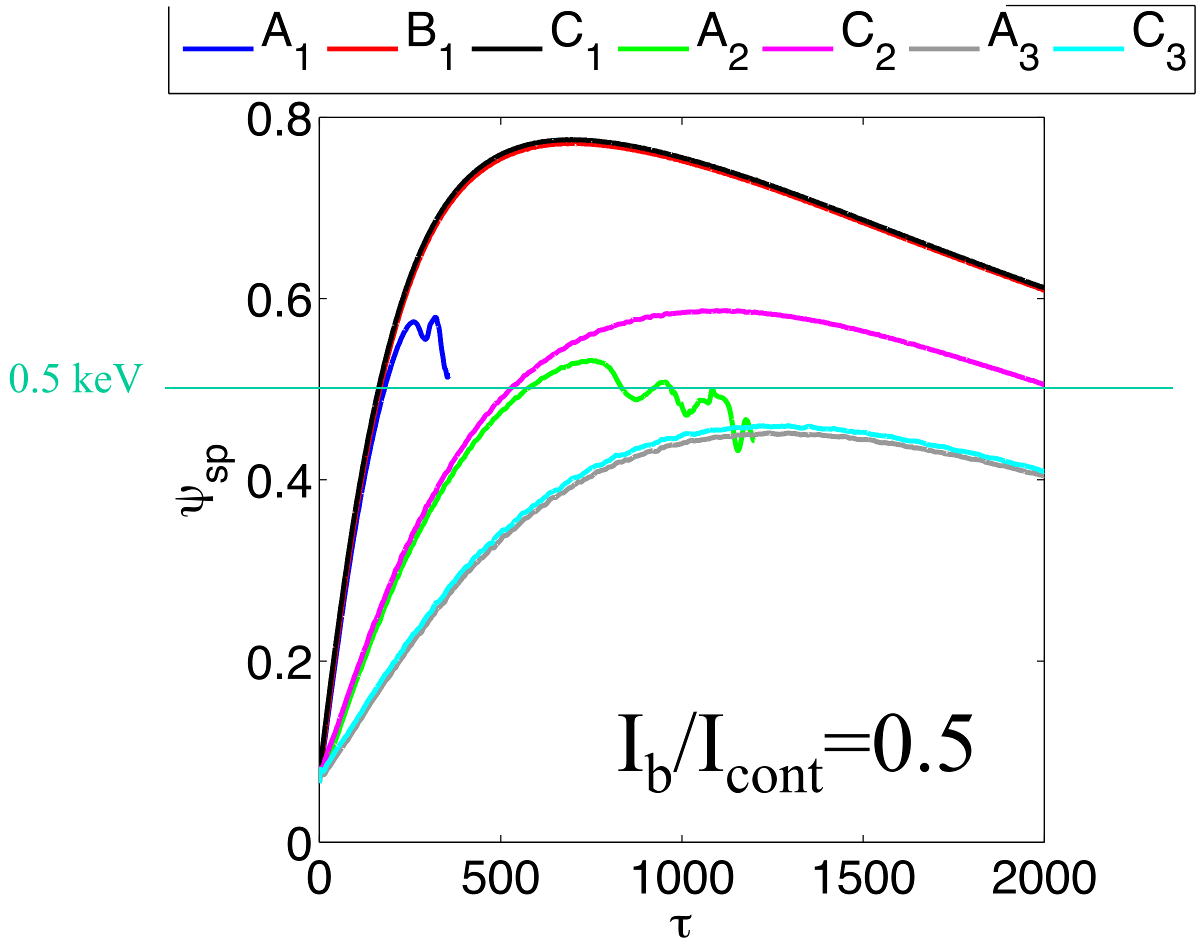
- PIC simulations:
contactor, spacecraft and beam
- Contactor fired before beam
    - 3 initial configurations with different size of contactor cloud
- Fire electron beam
    - with contactor on

- Contactor fails to draw a large current from bg

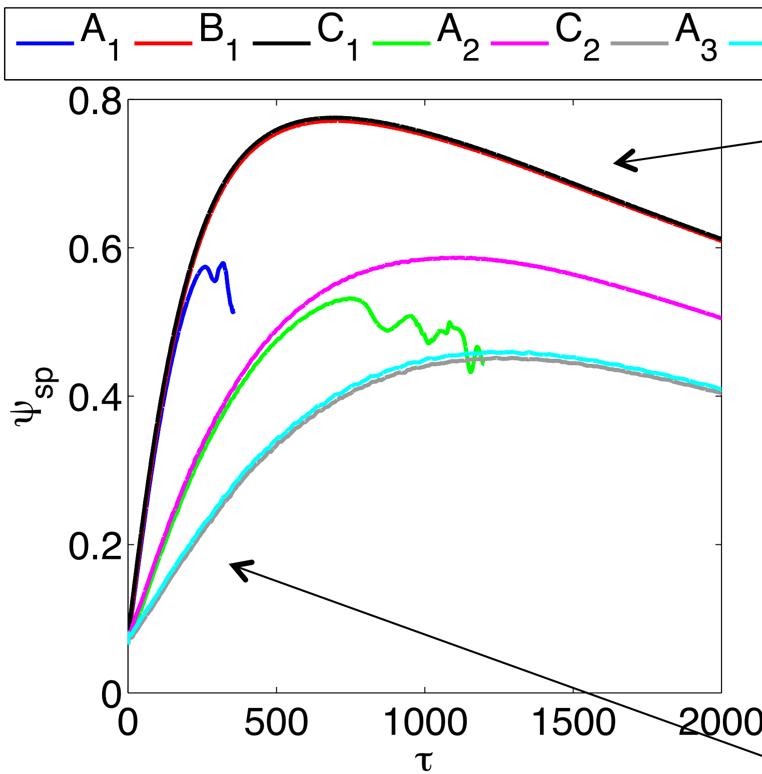


In a different parameter regime, I_b/I_{cont}<1, the beam can be emitted

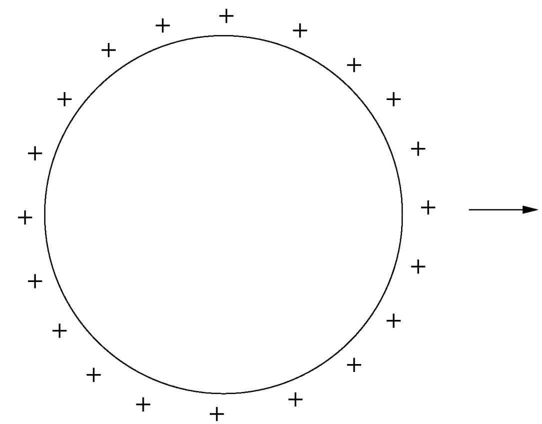
$$\frac{dQ_{sp}}{dt} = I_b^e + I_e^{bg} + I_i^{bg} + I_e^{cont} + I_i^{cont}$$



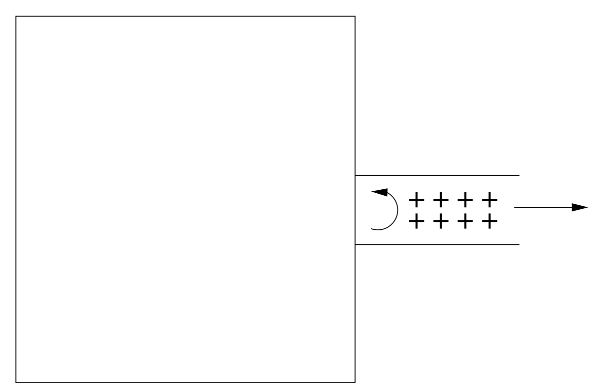
The physical explanation is the Child-Langmuir law: when the contactor cloud is sufficiently large, it emits more positive charge than the beam negative charge



Delzanno et al, JGR 2015a,b



(Quasi-)spherical geometry: not space-charge limited, emission of net positive charge enabled



Planar geometry: space-charge limited

Conclusions:

Curvilinear PIC (CPIC)*: a flexible, fully kinetic, 3D electrostatic PIC code in general curvilinear geometry for plasma-material interaction studies

- Features:
  - ✓ Optimal design choices
    - ✓ Non-uniform, structured meshes: fast solvers
    - ✓ Curvilinear formulation: particles move in uniform mesh
    - ✓ Optimal, scalable solver based on multigrid
    - ✓ Parallelized
  - ✓ Multi-block meshes
  - ✓ Enables tackling a broad set of plasma-material interaction problems

*Delzanno et al, IEEE Trans. Plasma Science (2013); Meierbachtol et al, in preparation (2016)